Arnold Schwarzenegger
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PHYSICAL ENERGY ACCOUNTING IN CALIFORNIA: A CASE STUDY OF CELLULOSIC ETHANOL PRODUCTION

PIER INTERIM PROJECT REPORT

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Preface

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- Transportation

Physical Energy Accounting for California is the interim report for the PHYSICAL ENERGY ACCOUNTING IN CALIFORNIA: A CASE STUDY OF CELLULOSIC ETHANOL PRODUCTION project (Contract Number 500-02-004, Work Authorization Number MRA 069) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to PIER's Energy-Related Environmental Research program.

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Abstract

California's target for greenhouse gas reduction in part relies on the development of viable low-carbon fuel alternatives to gasoline. It is often assumed that cellulosic ethanol—ethanol made from the structural parts of a plant and not from the food parts—will be one of these alternatives. This study examines the physical viability of a switchgrass-based cellulosic ethanol industry in California from the point of view of the physical requirements of land, water, energy, and other material use. Starting from a scenario in which existing irrigated pastureland and fiber-crop land is converted to switchgrass production, the analysis determines the total acreage and water supply available and the resulting total biofuel feedstock output under different assumed yields. The number and location of cellulosic ethanol biorefineries that can be supported is also determined, assuming that the distance from field to biorefinery would be minimized. The biorefinery energy input requirement, available energy from the fraction of biomass not converted to ethanol, and energy output is calculated at various levels of ethanol yields, making different assumptions about process efficiencies. The analysis shows that there is insufficient biomass (after cellulose separation and fermentation into ethanol) to provide all the process energy needed to run the biorefinery; hence, the purchase of external energy such as natural gas is required to produce ethanol from switchgrass. The higher the yield of ethanol, the more external energy is needed, so that the net gains due to improved process efficiency may not be positive. On 2.7 million acres of land planted in switchgrass in this scenario, the switchgrass output produces enough ethanol to substitute for only 1.2 to 4.0 percent of California's gasoline consumption in 2007.

Keywords: Cellulosic ethanol, ethanol, biofuels, switchgrass, biorefinery, irrigation, physical energy accounting

Executive Summary

The State of California has an ambitious set of goals to reduce emissions of greenhouse gases and other pollutants, increase fuel diversity, and slow down or reverse the rate of potential climate change and other forms of environmental degradation associated with economic and demographic growth (Franco et al. 2008). There are widespread expectations that mass production of cellulosic biofuels—biofuels made from the structural parts of a plant and not from the food parts—can contribute substantially to reaching these goals (Farrell et al. 2006). Studies evaluating the potential for large-scale biofuel production tend to focus on the economic costs under current conditions and fail to adequately address the far more fundamental issues associated with the physical viability of the required massive changes to current patterns of production and consumption. The method developed here defines the necessary allocation of resources based entirely on the physical requirements for production, conservation of mass, and the finite availability of land and water. The approach taken here is inspired by the use of foodweb analysis in the quantitative modeling of ecosystems. An ecosystem consists of a set of organisms in a particular region together with the surrounding physical environment. Members of an ecosystem interact in a wide variety of ways, but perhaps the most basic is that they eat, and are eaten by, one another. *Foodweb* is the term used to describe the network of relationships defined by who eats whom

Conceptually, this approach differs from existing analyses of energy balances in four ways. First, as in foodweb models, material inputs and outputs are measured in units of mass. Second, all energy use inside the ethanol plant is accounted for, and energy sources are categorized as internal or external. Internal energy sources come from the biomass feedstock that is recycled and burned at the plant. The fraction of feedstock that is available to be used as an energy source is deduced from mass conservation and places strict limits on the degree to which an ethanol plant could be energetically self-sufficient. Given this framework, various definitions of net energy return, efficiency, sustainability and so forth can be quantified as needed. Third, biofuel feedstock production is situated within the existing agricultural system in California. Growing crops for fuel in California competes directly with other agricultural production for water, as it cannot be grown without irrigation. This is true even though the biofuel feedstock is not itself a food crop. As a result, the potential production of ethanol within the state is strongly constrained. Fourth, the model includes the effect of possible efficiency improvements by examining the impact of improved agricultural yields and process efficiencies that are expected in the future.

Switchgrass (*Panicum virgatum)* was chosen in this study as the feedstock for California cellulosic ethanol production because of its high relative content of sugar-containing cellulose and hemicellulose (73 percent) to woody lignin. Switchgrass is a warm-weather perennial grass native to summer-rainfall areas of the United States and found in most states east of the Sierra Nevada. It was a major grass component of the original Great Plains before agricultural disturbance. As a grassland native, it tolerates a wide range of temperature and rainfall conditions and is fairly pest resistant. Current production methods have resulted in yields of about 3 tons/acre[1]; the study also examines the impact of yields at 4, 5, and 6 tons/acre.

For this study, it was assumed that switchgrass would be grown only on irrigated land. For economic reasons, only irrigated pastureland and fiber crops are likely to be displaced by switchgrass in California. The amount of land that could potentially be converted to switchgrass is determined by estimating the water currently used for irrigating pasture and fiber crops, and switchgrass water needs in the California climate. This results in a total acreage planted of 2.7 million acres.

The analysis includes a method to determine the number and location of ethanol plants that would be needed to process the total switchgrass output. The plants are located to minimize the distance traveled by the feedstock to get to the biorefinery. The capacity of the biorefinery is assumed to be 40 or 50 million gallons (MGal)/year ethanol output, depending on the biorefinery process efficiency. The 50 MGal/year capacity is comparable to the typical size of new corn ethanol plants. At lower process efficiency, a larger volume of fluid must be processed per gallon of ethanol out. Assuming the refinery design is determined by the total liquid throughput results in a capacity for the lower efficiency process of 40 MGal/year. Several scenarios combining different assumptions about crop yields and biorefinery efficiencies are analyzed in detail. The number and location of biorefineries depend on the scenario.

No fully commercial-scale cellulosic ethanol biorefineries exist from which detailed breakdowns of process energy and water requirements can be obtained. Current estimates of total-plant energy consumption are about 27-29 megajoules (MJ) per liter (l) of ethanol output. This analysis uses a value of 27 MJ/l (about 97,000 British Thermal Units (BTUs)/gallon). A number of authors assume that the lignin in the switchgrass is not only sufficient to provide all the energy needed in the biorefinery at this level of biorefinery energy consumption, but also can generate surplus electricity for sale. This study shows that this is not the case.

Two biorefinery efficiency scenarios are considered here. Average efficiency assumes that the rates of recovery of the sugar-containing cellulose fractions and rates of fermentation efficiency are equal to values that can be obtained using the best available current technology. At this efficiency, output is 240 liters of ethanol per tonne of switchgrass (58 gallons per ton). In the high-efficiency case, recovery and fermentation efficiencies are set at 90 percent, leading to an output of 350 liters of ethanol per tonne of switchgrass (84 gallons per ton). The cellulose, hemicelluloses, and lignin fractions of an input kilogram of switchgrass are tracked as the material proceeds through the biorefinery, so that the resulting ethanol yields, waste products, and quantity of material that can be burned to provide energy for the plant are consistent with the basic requirement that mass be conserved. Using this method, it is shown that the biomass available as a fuel source inside the biorefinery is sufficient to provide about 85 percent of the total energy requirement at average efficiency, and about 55 percent of the energy of the plant at high efficiency. The remainder must be supplied as external energy-natural gas or purchased

[1] In this report, the unit "ton" in all cases refers to the U.S. short ton of 2000 pounds. The unit "tonne" refers to a metric tonne of 1000 kilograms, or 2,205 pounds.

electricity. As efficiency of production increases, the energy deficit grows more rapidly than the energy content of the additional ethanol output, so that the net benefit of efficiency gains under these conditions is questionable. Also, as the amount of external energy grows (for example, using natural gas), more of the carbon savings from using switchgrass may be reduced.

Energy requirements for moving the switchgrass to the refinery and distributing the ethanol product are also calculated. Each biorefinery would, on average, require the delivery of 100 to 110 truckloads of switchgrass per day. Because switchgrass is harvested only once or twice a year—with a single harvest after autumn resulting in the lowest loss of nutrients—deliveries would be highly seasonal and likely concentrated in the autumn and early winter months. The implication of seasonal delivery is the requirement for large areas of biomass storage at the biorefinery. For ethanol delivery, it was assumed that liquid fuel tanker trucks would deliver ethanol from the biorefinery to the closest fuel distribution terminal, each truck carrying 9,000 gallons of fuel. In the low case scenario that was examined (low switchgrass yields and average ethanol yields), total transport energy reached about 3.4 petajoules (PJ) (approximately 23 million gallons of diesel). In the high case scenario that was examined nearly 7 PJ (approximately 48 million gallons of diesel) of transport energy was consumed. Cellulosic ethanol plants are also water-intensive, requiring about 12-15 gallons of water per gallon of ethanol output[2]. As a result, the energy required for conveyance and wastewater treatment is approximately 20 percent of the total energy use estimated for transportation.

The capital recovery cost[3] per gallon of cellulosic ethanol is estimated to be three times that of corn ethanol plants (Tiffany 2005), and the energy costs about twice the proportion of that in corn ethanol plants. This means that, to compete with corn ethanol, the feedstock cost of cellulosic ethanol plants cannot be more than 30 percent of the selling price of ethanol. The current rack or wholesale price for ethanol is $2.59/gallon[4], implying that farmers would get no more than about $130 to $185 per acre or up to $250 to $360 per acre at high yields and plant efficiency, compared to an estimated $300 per acre for field crops. For most of the scenarios, the implication is that a farmer selling switchgrass to an ethanol plant would earn less per acre than they would growing wheat or hay. On the other hand, if the farmer is paid a competitive price for switchgrass, cellulosic ethanol (under current conditions) could not likely be competitively priced.

[2] This depends on the particular process used. This study assumes dilute acid hydrolysis is used to convert the cellulosic material to sugars.

[3] This is the cost of building the biorefinery, including financing, amortized over the lifetime of the facility.

[4] April 2008 rack price, Nebraska, as reported monthly at http://www.neo.ne.gov/statshtml/66.html

Benefits to California

In 2007, California consumed 15.7 billion gallons of gasoline. Under the assumptions in this study, total cellulosic ethanol output from the diversion of 2.7 million acres of irrigated pastureland to switchgrass production could supplant from 1.2 percent to 4.0 percent of total current gasoline consumption. The results of this study benefit California by helping policy makers have better information for decisions regarding the allocation of resources toward developing feedstocks and infrastructure for biofuels to diversify fuel supply and reach greenhouse gas emission reduction targets.

1.0 Introduction

The State of California has an ambitious set of goals to reduce emissions of greenhouse gases (GHG) and other pollutants, increase fuel diversity, and slow down or reverse the rate of potential climate change and other forms of environmental degradation associated with economic and demographic growth (Franco et al. 2008). There are widespread expectations that mass production of cellulosic biofuels can contribute substantially to reaching these goals (Farrell et al. 2006). Loosely, the idea behind cellulosic biofuels is to synthesize gasoline substitutes such as ethanol from the cellulose in non-food plant material, for example grasses or wood waste. Currently, the only production of ethanol on a commercial scale is from corn or other sugar-containing plants. While the conversion of sugars to ethanol is well understood, the chemical processes required to convert cellulose to a suitable fuel are far more complex, and as yet no operational commercial plants exist. Nonetheless, there have been many studies evaluating the potential of cellulosic biofuel production. These potential studies tend to assume optimistic future conditions and stable prices. The expected benefits of biofuel production are due primarily to the fact that the feedstock is a renewable resource, and the carbon emissions from burning biofuels are reduced relative to the burning of fossil fuels. Two key questions that remain open are whether cellulosic biofuel production can be scaled up quickly enough to have a significant impact on the environmental problems related to fossil fuel use, and whether this approach is optimal from a societal perspective (Russi 2008).

Large-scale production of biofuels will have large impacts on the existing use of resources in the productive economy: on the input side, demand for new resources or displacement of existing resources from their current uses, and on the output side, supply of new commodities (transportation fuels and possibly other useful byproducts). Economic methods are typically used to evaluate the costs and benefits of this type of reallocation of resources, especially for policy-oriented research. In economic models, all the quantities of interest are assigned prices, and the utility of a policy is evaluated in terms of its net cost or benefit in dollar terms. This is a reasonable approach if the changes under consideration are small, but can be misleading if the changes are large enough to affect the existing price system, or to bring in non-economic factors in a significant way. In looking at energy development for the future, both the amount of time it will take to implement new policies, and the degree to which choices are limited by hard physical constraints (such as water availability, or limitations on emissions) will be increasingly important. Standard economic models are not set up to handle these types of issues in a straightforward way.

In this study, some new ideas on how to approach the problem of allocating resources under potential large changes to the energy system are presented, with a focus on physical quantities, constraints and conservation laws. These are applied to an analysis of the output potential for cellulosic biofuel production in California. To provide a reference framework for what constitutes a reasonable set of assumptions, the analysis considers only processes that are well-defined enough that they could conceivably be implemented within a time frame of ten years.

1.1. Energy Accounting and Foodweb Modeling

Numerous authors have looked at the general economic, environmental and resource impacts of a large-scale shift from fossil fuels to biofuels (Badger 2002, Hammerschlag 1999, Farrell et al. 2006, Patzek & Pimentel 2005, Russi 2008, Wu et al. 2005). Given the complexity of the problem, it is difficult to define simple numerical measures that can be used to compare different options. One metric that is often used is the net energy return. This is intended to be a measure of whether a project is "worth it" in energy terms—if more energy is used up in the production process than is contained in the end product, one can legitimately question the overall utility of the exercise. Public discussion of these issues is hampered by the fact that different authors may use inconsistent definitions of the concept of net energy. For example, some authors include the energy contained in byproducts of the production process in the net energy calculation, even though those byproducts are not used as fuel (Farrell et al. 2006). Materials with no market value (such as the crop stubble left in a field after harvest) may also be treated inconsistently in different analyses. Another contentious issue is how to define the boundaries of the system being analyzed. The production chain for biofuels is complex, with a wide variety of inputs used in growing, harvesting, and handling the biomass feedstock, and processing and distributing the output. The selection of what to include and what to ignore can have a significant impact on the numerical results of the analysis.

One of the goals of this study is to contribute to the development of a coherent logical framework for analyzing large-scale, non-incremental changes to the energy system, within which such questions about system boundaries, net energy gains *etc.* can be given a consistent, clearly motivated answer. The approach taken here is inspired by the use of foodweb analysis in the quantitative modeling of ecosystems. An ecosystem consists of a set of organisms in a particular region together with the surrounding physical environment. Members of an ecosystem interact in a wide variety of ways, but perhaps the most basic is that they eat, and are eaten by, one another. *Foodweb* is the term used to describe the network of relationships defined by who eats whom (Drossell & McKane 2002, Schoener 1989). Biologically, food is a source of energy, so a foodweb can also be thought of as a map of the flow of energy and material through the ecosystem. This more abstract view is used here to develop a comparable system of physical energy accounting in the economy, as summarized below. A detailed discussion of foodweb modeling and how it might apply to the economy is given in Appendix A.

The foodweb approach characterizes species in terms of their dominant predators and food sources, and categorizes them into hierarchical set of groups known as tropic levels. The lowest trophic level in a foodweb consists of resources taken directly from the environment. At this level, constraints on the availability of land, water, sunlight, soil nutrients *etc.* are quantified. The growth of organisms at higher levels depends both on the availability of food from lower levels and the degree to which predation from consumers at higher levels depletes the population. A key feature of this modeling framework is that the inputs at the lowest level, upon which the whole system is built, are finite. This means that there will generally be trade-offs between the growth of some species and the decline of others.

The focus on the interactions and flow of energy required to sustain an assemblage of populations provides useful criteria for defining system boundaries and determining what does and does not need to be modeled explicitly in an analysis. In ecology, an ecosystem is tied to a particular geographic place. The system boundary is defined in spatial terms such that, for the processes under consideration, the flow of material or energy across the boundary is not large (compared to flows within the boundary). Given a fixed spatial boundary as part of the analytical framework, it is then straightforward to create an inventory of the land and water resources available, and to deduce how these constrain the production potential under various scenarios.

In ecosystem modeling, the question of what processes to include in an analysis depends on the species of interest, and the strength of its interactions with (i.e. eating and being eaten by) other species. For policy analysis, these questions depend both on the goals of the analysis and on how the baseline situation is defined. The specific approach taken for the cellulosic biofuel analysis is outlined in the next section.

1.2. Project Approach

For this study, the spatial system boundary is defined as the California border. This means that both the farms producing the biofuel feedstock and the processing plants (or biorefineries) are assumed to be located within the state. Within California, information about existing land use and water resources is used to determine the potential output of cellulosic feedstock. For definiteness, we assume that this crop will be switchgrass. As there is essentially no rain in California during the summer months, growing switchgrass will require irrigation water, so biofuel feedstock production must compete with other agricultural sectors in the state for the use of irrigated land. This constraint defines the limit of total cellulosic production potential.

The agricultural production of feedstock constitutes the lowest level in the foodweb analogy. The model of conversion of the input biomass to the output ethanol is constructed as a "food chain" through the various processing steps, with mass conservation imposed at each stage. This approach clarifies the relationship between the yield of ethanol per unit of biomass and the parameters that define the efficiencies of the different processing steps. This is essential because the production of cellulosic biofuel on an industrial scale is still a hypothetical enterprise. The processes involved are the subject of continuing research, and process efficiencies are not known with certainty. The methodology used here allows the dependence of output on these unknown parameters to be quantified. A range of values, based on current demonstration projects and stated research project targets, are used to generate a series of scenarios. The analysis also includes four agricultural yield scenarios.

For the purpose of energy accounting, a given biofuel production scenario should be compared against a baseline. Here, because growing the feedstock requires the reallocation of irrigation water from existing uses, the obvious baseline to use is the existing agricultural production system. Only *changes* to resource use (*i.e.* new activities) need to be added to the energy cost of producing biofuels. Lost production of other agricultural commodities should also be included in the accounting system, but are not considered in detail in this report as they do not affect the energy balance. New energy-consuming activities include transportation of the feedstock and ethanol, biorefinery processing, and wastewater treatment. The energy required to supply irrigation water, and the labor and related farm outlays, are not included as they are displaced from existing uses.

In this system, only actual fuels are converted to equivalent energy units and included in the energy balance. This is a logically consistent implementation of the foodweb modeling approach. The role a commodity plays in the overall system depends on how it enters into production and consumption activities. Only commodities that can actually substitute for one another in a functional sense should be converted to equivalent units and accounted for under the same heading. Here, the analysis is concerned with transportation fuels, so only commodities used in the production process that are potential substitutes for transportation fuels are included in the energy balance. This includes natural gas and electricity, since a variety of transportation systems can use these fuels.

Conceptually, the approach used in this study differs from existing analyses of energy balances in several ways. First, as in foodweb models, material inputs and outputs are measured in units of mass. Mass is directly observable with low uncertainty, and production levels measured in mass can be related in a straightforward way to other physical quantities. Second, all energy use inside the biorefinery is accounted for, with energy sources categorized as internal or external. Internal energy sources come from biomass feedstock that is recycled and burned at the plant. The fraction of feedstock that is available to be used as an energy source is deduced from mass conservation, and places strict limits on the degree to which an ethanol plant could be energetically self-sufficient. Given this framework, the net energy return can be quantified without ambiguity. Third, biofuel feedstock production is situated within the existing agricultural system in California. Growing crops for fuel in California competes directly with other agricultural production for water, as it cannot be grown without irrigation. This is true even though the biofuel feedstock is not itself a food crop. As a result, the potential production of ethanol within the state is strongly constrained irrespective of future improvements to the conversion process. Finally, the model quantifies the effect of possible efficiency improvements by using parameters to describe the process efficiencies that are the subject of ongoing research. This allows the material benefit (in terms of increased ethanol yield) to be calculated and compared to the energy and material cost of implementing the improved process.

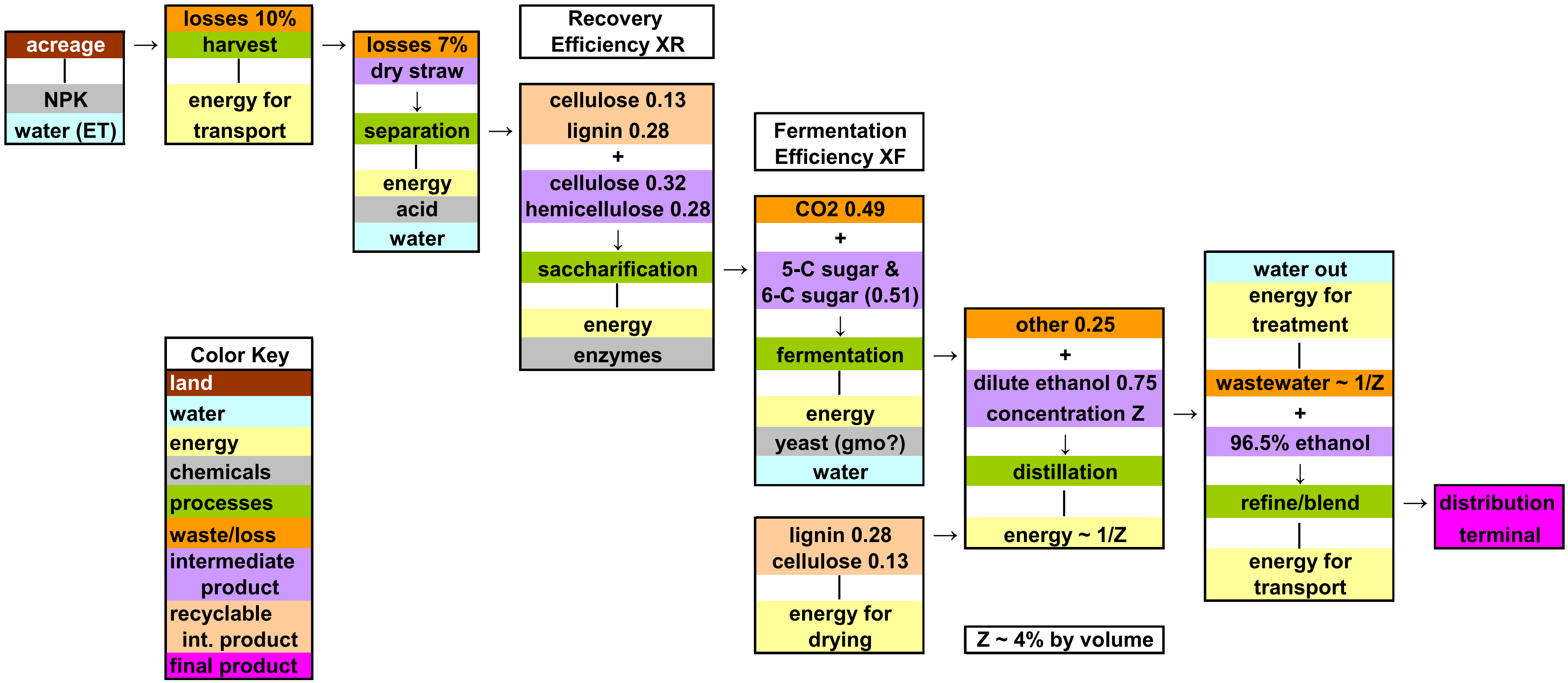

Figure 1. Ethanol Process Accounting Schematic

2.0 Case Study: Switchgrass-Based Ethanol Industry

2.1. Ethanol Process Accounting

This section describes the accounting scheme as illustrated in Figure 1, which shows the processing stages required from the farm to the final gasoline distribution plant. This analysis goes into quite a bit of detail about what happens inside a hypothetical cellulosic ethanol plant, both to clarify the energy accounting, and because of the need to parameterize plant efficiencies. The boxes in the figure are color-coded, with green representing processes. The boxes lined up in a vertical column represent the inputs and outputs from each process step: intermediate products that pass to the next step (purple), intermediate products that can be recycled as fuel (tan), and losses and waste products (orange). Water requirements are indicated by blue boxes, industrial chemicals by grey, and process energy by yellow boxes. The fuel type used to generate process energy is not shown on this diagram. While the fuel type is important for engineering design, as far as physical accounting goes, only an estimate of the energy requirement is needed.

The most important stages of the process are itemized below, and treated in more detail in subsequent sections.

1. Grow and harvest the feedstock. This requires land, water and fertilizer as inputs. The output is dried biomass which must be transported to the ethanol plant for processing.

2. The first of five steps within the ethanol plant is *separation* of the feedstock into cellulose and hemicellulose which can be converted to ethanol, and lignin which can be burned as fuel. This step is assumed to proceed by dilute acid hydrolysis (BJCE 1997) which requires water and sulphuric acid. The fraction of cellulosic material that is recovered to be passed to the next stage is parameterized by X_R.

3. The next step is the process of breaking (hemi) cellulose into its components (*saccharification* process). This produces sugars which can be fermented to produce ethanol.

4. The sugars are converted to ethanol by *fermentation.* The other byproduct is CO_2. The fraction of material that is successfully fermented is parameterized by X_F.

5. Fermentation produces a dilute beer that is *distilled* to increase the concentration of ethanol. The concentration of ethanol by volume in the beer is defined as Z. Distillation is energy intensive with the energy required roughly proportional to 1/Z. This step also produces a volume of wastewater proportional to 1/Z.

6. The maximum concentration of ethanol that can be produced by distillation is 96.5%. To reduce the water content further to the required maximum of 1% as specified by the ASTM (American Society for Testing and Materials) specifications for fuel alcohol requires *dehydration.* This and subsequent steps in the process are independent of the feedstock used.

7. The final step is transportation of the ethanol to a distribution terminal, where it enters the distribution chain as a gasoline substitute.

2.2. Feedstock Selection

Switchgrass was chosen in this study as the feedstock for California cellulosic ethanol production because of its high relative content of cellulose and hemicellulose to lignin. On average, each kilogram of switchgrass contains 42% cellulose, 31% hemicellulose, and 28% lignins, along with small amounts of ash (Isci 2008). Corn stover, also considered a possible cellulosic ethanol feedstock, is more variable in content and contains 35-40% cellulose, 20-25% hemicelluloses, 11-19% lignin, and 2-16% ash (Sheehan 2001).

Switchgrass (*Panicum virgatum)* is a warm-weather perennial grass native to summer-rainfall areas of the United States and found in most states east of the Sierra Nevada. It was a major grass component of the original Great Plains prior to agricultural disturbance. As a grassland native, it tolerates a wide range of temperature and rainfall conditions and is fairly pest resistant.

Switchgrass has been the subject of several large-scale multi-year field studies on yield potential and application. One of the earliest was the Chariton Valley Biomass Project, first organized in 1996 and later funded by the US Department of Energy's Biomass Power Program. Switchgrass was grown on 4,000 acres of Conservation Reserve Program (CRP) land in southern Iowa, with the aim of providing switchgrass for co-firing with coal in a local power plant. By 2005, Chariton Valley reported a switchgrass average yield of 4 tons/acre (9 tonne/hectare), with expectations of increasing the yield to 6 tons/acre (13.5 tonnes/hectare) in the future (CVBP 2005).

A second multi-year trial involved four farms in Nebraska, four in South Dakota and two in North Dakota, covering 165 acres in total planted in switchgrass. Each farm managed the switchgrass plantings as a commercial crop, applying herbicide treatment at the initial planting, along with inputs of nitrogen, potassium and phosphorus fertilizers. The trial covered five years and accounted for all agricultural and field inputs to production. Harvests started in the third year after planting and continued for two additional years. Over the three years of harvest in the 10 farms, mean switchgrass yield reached 3.2 tons/acre (7.1 tonnes/hectare) (Schmer 2008).

Based on these trials, four yield levels were chosen for the study in order to test the impact of varying yield levels on raw material supply and ethanol production. The four yield levels tested were 7, 9, 11, and 13.5 tonnes/hectare (3.1, 4.0, 4.9, and 6 tons/acre).

2.3. Land and Water Requirements

Land and water allocation are determined based on data from the California Department of Water Resources (DWR). The DWR conducts periodic land use surveys by county, which provide highly-resolved spatial data on land use, crop type, irrigation method etc. (DWR 2008a). A representative survey for Fresno County is shown in Figure 2. In this image, each field is color-coded by land-use or, for agricultural land, by crop type. These data were used to determine, for each county, the total acreage by crop type and whether the land was irrigated. The DWR surveys include a category "native vegetation" that represents land that is not cultivated or used for any non-agricultural purpose.

Switchgrass requires water during the summer, so presumably will only be grown on land that is already irrigated. As the real limitation is water, to estimate the potential switchgrass acreage requires several steps as follows:

- Estimate the amount of irrigation water currently used by county and by crop type. This is equal, for each crop type, to the acreage by county multiplied by the annual applied water per acre. The latter is available from DWR land and water use data tables (DWR 2008b).
- Estimate the annual water need for an acre of switchgrass by county. The methodology used is explained in detail below.
- Because irrigation is necessary, the scenario developed here assumes that irrigated land for the production of high-value food crops would not be converted to switchgrass production; only water used for relatively low value crops will actually be diverted. This includes land used for pasture and hay production and, where diverted water is sufficient, additional land in native vegetation is converted.
- For each county, the total irrigation water available is equal to the acreage in pasture and hay multiplied by the applied water per acre for these crop types.
- The total acreage that can be converted to switchgrass is equal to the total water available divided by the water need per acre. Irrigation efficiency is set at 85%.
- If the total acreage that can be converted to switchgrass exceeds the acreage currently planted in pasture or hay, it is assumed that native vegetation is converted as needed.

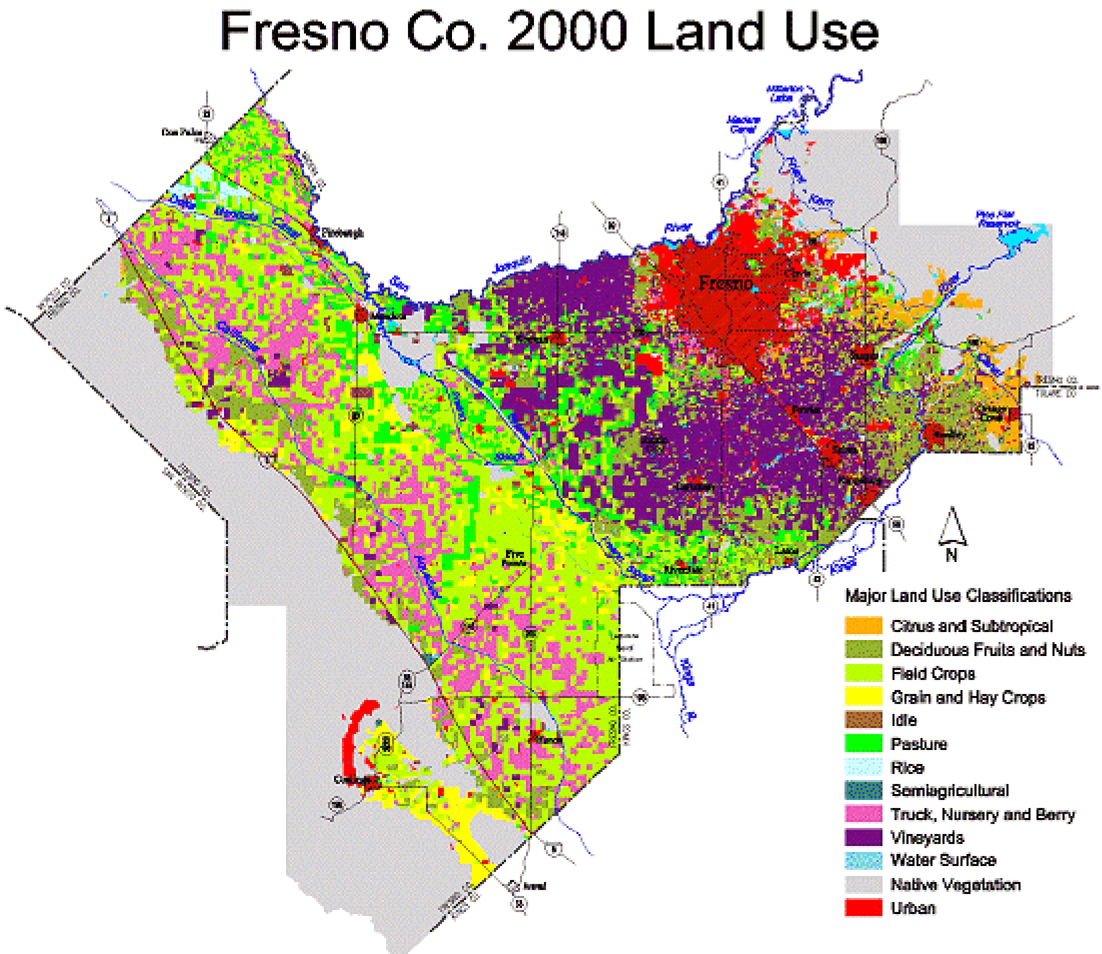

Figure 2. DWR Land Survey Map for Fresno County
Source: Lawrence Berkeley National Laboratory

This approach leads to a total of approximately 2.7 million acres available to be planted in switchgrass, primarily in the Central Valley.

To determine the irrigation requirement for switchgrass, each county was assigned a primary and, where necessary, a secondary evapotranspiration (ET) zone based on the 18 ET zones defined by the DWR (DWR 1999). For each ET zone, monthly data compiled by the Irrigation Training and Research Center (ITRC 2005) were used to compile average precipitation, reference crop ET, and ET for "Pasture and Miscellaneous Grasses". From these data the total amount of applied water needed during the growing season can be calculated, assuming that switchgrass water needs are comparable to "Pasture and Miscellaneous Grasses."[5]

It was assumed that switchgrass plantings would be sprinkler irrigated with an irrigation efficiency of 85%. The total volume in acre-inches of irrigation water originally used on the

[5] A nine-year study of the ET of prairie tall grasses in Kansas measured a reference crop coefficient of about 1 (Hutchinson 2001). It is assumed California performance would be similar.

supplanted pasture and fiber-crop land was then divided by total annual precipitation deficit and the sprinkler irrigation efficiency of 85% to determine the total number of acres in each county that could be converted to irrigated switchgrass cultivation (Figure 3, Table 1).

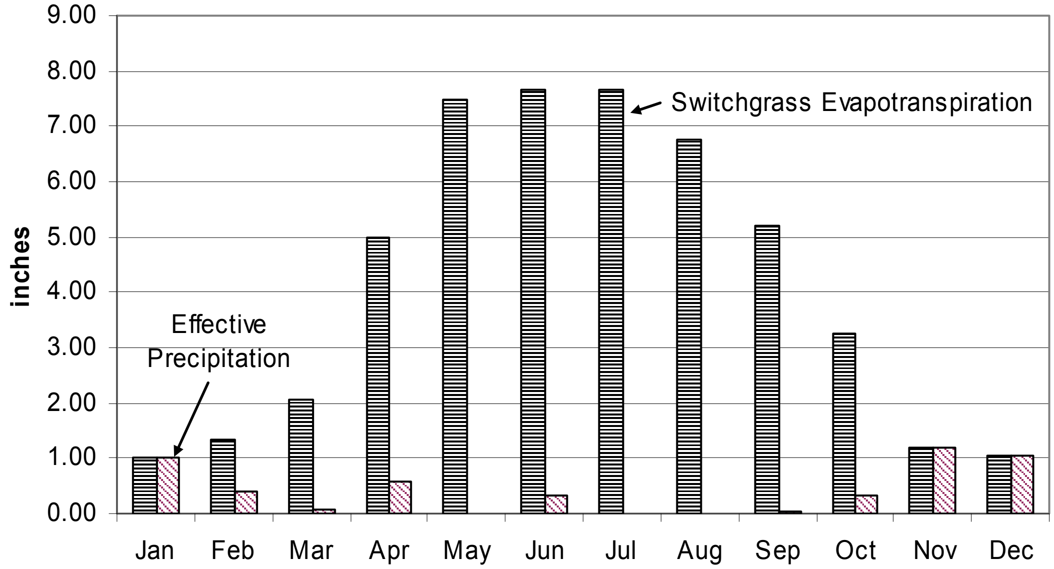

Figure 3. Effective Precipitation and Evapotranspiration for ET Zone 15 (Fresno Co)

Source: Lawrence Berkeley National Laboratory

Table 1 Precipitation Deficit Calculation for Zone 15 (Fresno Co)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Precipitation	3.46	0.39	0.07	0.59	0.01	0.33	0.01	0.00	0.02	0.33	1.91	1.28	8.40
Switchgrass ET	1.02	1.35	2.05	5.00	7.49	7.66	7.68	6.75	5.20	3.25	1.19	1.05	49.69
Effective Precipitation	1.02	0.39	0.07	0.59	0.01	0.33	0.01	0.00	0.02	0.33	1.19	1.05	5.01
Precipitation Deficit	0.00	0.96	1.98	4.41	7.48	7.33	7.67	6.75	5.18	2.92	0.00	0.00	44.68

2.4. Allocating Switchgrass Production to Biorefineries

Ethanol plants were assigned to counties based on the total switchgrass output and the plant feedstock requirement, using a method that attempts to minimize the distance traveled by the feedstock to get to the biorefinery. The capacity of the biorefinery is assumed to be 50 MGal/year (189 Ml/year) ethanol output in the high efficiency case, and 40 MGal/year (151 Ml/year) in the average efficiency case. The value 50 MGal/year is comparable to the typical size of new corn ethanol plants (ACE 2008). At lower process efficiency, a larger volume of fluid must be processed per liter of ethanol out. Assuming the refinery design is determined by the total liquid throughput, the output for the average efficiency process would be about 40 MGal/year.

For each scenario, an iterative method is used to locate plants in counties until either all the biomass has been allocated, or the distances involved are too large. The total feedstock requirement is determined by the biorefinery output and the process efficiencies, while the geographic distribution of feedstock varies with agricultural yield. This means that the locations chosen for biorefineries will differ in different scenarios. In the first step of the algorithm, plants are located in any county that produces sufficient feedstock to support one or more biorefinery. The biomass that is allocated to these plants is then deducted from the total. In the next step, as there are no single counties that can support a plant, for each county the total available biomass in its *neighborhood* is calculated. The neighborhood of a county is defined as the set of counties with which it shares a border. The next set of plants is put into the county that has the largest amount of biomass in its neighborhood. Biomass is allocated from the neighboring counties until the plant requirements are met, this allocation is deducted from the total remaining, and the process is repeated. The algorithm stops when no county has enough biomass in its neighborhood to support a plant. With this method, roughly 10% of the total agricultural output ends up stranded (unable to be used at a plant). The exact fraction of biomass that can be used varies slightly in different scenarios.

Once the biorefineries have been sited and the feedstock source counties identified, it is straightforward to calculate the average distance traveled by each tonne of feedstock on its way to the plant. In this calculation, the distance between neighboring counties is approximated as the sum of the square-roots of their areas. This is a rough distance metric that doesn't take into account the topology of the highway system, and is likely to be an under-estimate. For each biorefinery, the total mass coming from a given county times the distance to that county is calculated in tonne-kilometers, and the figure is summed over all counties contributing feedstock to a single plant. Dividing the total tonne-kilometers from all supplying counties by the total feedstock used at the plant gives the average distance traveled by each tonne of input feedstock. This value is used below to calculate the feedstock transportation energy use.

2.5. Plant Process Parameters and Mass Balance

No fully commercial-scale cellulosic ethanol plants exist from which detailed breakdowns of process energy and water requirements can be obtained. For segments of the process (fermentation, distillation and dehydration) that are the same as corn ethanol refineries, the basic parameters impacting total energy consumption, such as initial alcohol concentration of the beer, are better understood. Less well understood are the energy requirements for decrystallization, hydrolysis, acid-sugar separation and neutralization (Figure 4).

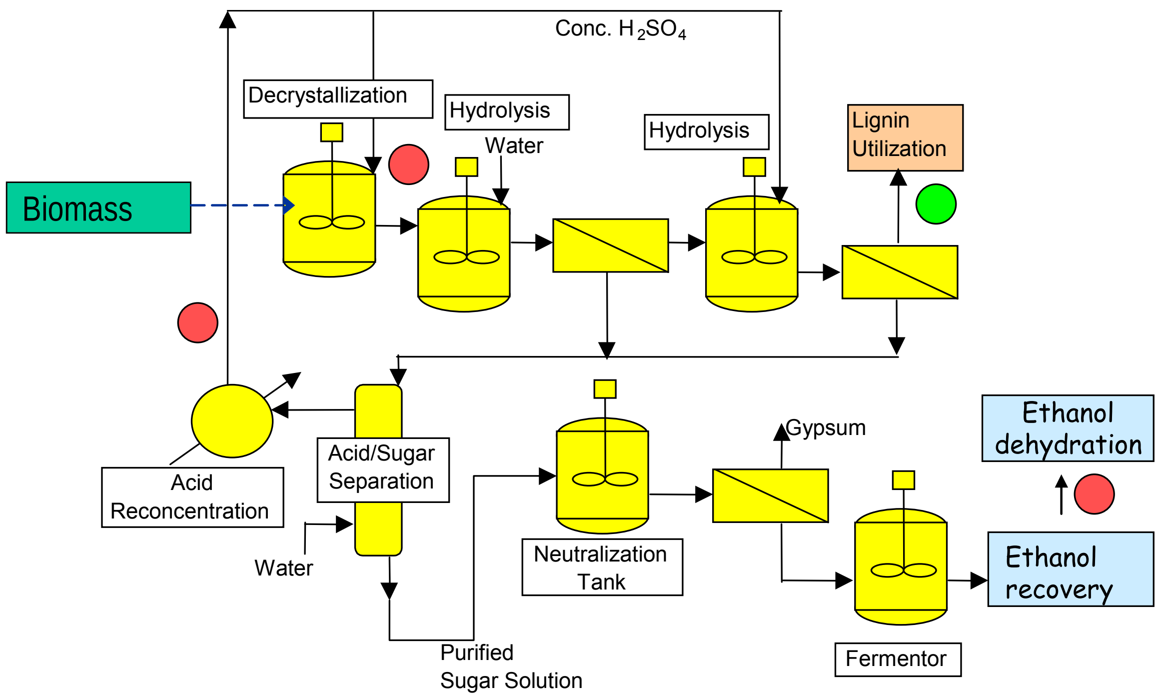

Figure 4. Conceptual Schematic for Biomass Ethanol Plant

Source: Somerville 2006

A number of studies provide estimated calculations of total-plant energy consumption as part of analyses of potential energy return of cellulosic ethanol production. Pimentel et al. (2005) estimated plant energy requirement at 29 megajoules/liter (MJ/l) of ethanol output, assuming 400 liters of ethanol output per tonne of switchgrass input, divided between 20.1 MJ/l of fuel and 8.9 MJ/l of electricity. In contrast, Sheehan (2004) assumes that all process energy can be provided by the biomass fraction remaining after separation of the sugars, but does not indicate the actual energy requirement. Farrell et al. (2006) offers a figure of 27 MJ/l energy (28 MJ/l including transport of biomass to the refinery and the embodied energy in the capital equipment in the refinery) consumption in the biorefinery phase assuming 380 liters of ethanol output per tonne of switchgrass input but also assume the process energy can be provided by the remaining lignin fraction of the input biomass.

For the purposes of this study, and in the absence of an adequate characterization of process-level energy requirements for a cellulosic ethanol plant, total plant consumption is assumed to be 27 MJ/l as used in the Farrell et al. (2006) study. In an actual commercial plant, this figure would vary depending on the initial concentration of the beer, the efficiency of lignin and cellulose/hemicellulose separation, the efficiency of fermentation, the volume of liquids moved, drying energy, and acid concentration, among others.

The mass balance within a cellulosic ethanol plant first considers the composition of the feedstock. Using a typical figure for switchgrass composition from Isci (2008), one kilogram of switchgrass input was tracked through the main process steps in the biorefinery to determine the balance of outputs, accounting for all fractions of the original feedstock through production of the final product (Table 2).

Table 2 includes two scenarios of process efficiency: an "Average" scenario based on current feasible technology and enzymes, and a "High" scenario in which the key parameters for increasing ethanol yield improve substantially, although not quite to the levels assumed in Farrell et al. (2006), where the implied efficiencies of all parameters reach 90%.[6]

Currently, an average recovery factor of hemicellulose has already reached 90%, but that of cellulose remains lower, largely because of the more complex bonds between the cellulose and lignin molecules and greater difficulty at separation. Cellulose molecules yield mainly six-carbon glucose, while hemicellulose contains primarily five-carbon xylose and arabinose, and some six-carbon galactose, glucose, and mannose. Because xylose is the principle sugar of switchgrass hemicellulose, it is used to represent the entire hemicellulose sugar fraction.

To determine the potential yield of ethanol from the recovered cellulose and hemicellulose fractions, the stoichiometric yield of ethanol (51% ethanol; 49% CO_2) is multiplied by the fermentation efficiency of the glucose and xylose. Average glucose fermentation efficiency is about 75 percent, but the more complex five-carbon sugars of hemicellulose have presented a significant challenge to high fermentation efficiencies, averaging around 50% (Badger 2002).

[6] These efficiency parameters are not explicit in Farrell et al. (2006) but result in an ethanol yield of 0.38 l/kg as assumed in the report.

Table 2. Mass Balance of One Kilogram of Switchgrass Under Two Process Scenarios

	Average Scenario		High Scenario	
Cellulose				
Cellulose content	0.42*	kg	0.42	kg
Recovery Efficiency	76%		90%	
Ethanol Stoichiometric Yield	51%		51%	
Glucose Fermentation Efficiency	75%		90%	
Ethanol from Glucose	0.12	kg	0.17	kg
Ethanol from Glucose	0.15	liters	0.22	liters
CO_2 emissions	0.15	kg	0.19	kg
Unrecovered cellulose in lignin	0.10	kg	0.04	kg
Other (bacteria mass growth, wastes)	0.04	kg	0.02	kg
Hemicellulose				
Hemicellulose content	0.31*	kg	0.31	kg
Recovery Efficiency	90%		90%	
Ethanol Stoichiometric Yield	51%		51%	
Xylose Fermentation Efficiency	50%		70%	
Ethanol from Xylose	0.07	kg	0.10	kg
Ethanol from Xylose	0.09	liters	0.13	liters
CO_2 emissions	0.08	kg	0.11	kg
Unrecovered hemicellulose in lignin	0.03	kg	0.03	kg
Other (bacteria mass growth, wastes)	0.13	kg	0.07	kg
Total Ethanol Yield	**0.24**	**l/kg**	**0.35**	**l/kg**
CO_2 By-product Emissions	**0.23**	**kg**	**0.29**	**kg**
Lignin and Other Balance				
Lignin content	0.28*	kg	0.28	kg
Energy Content**	6.4	MJ	6.4	MJ
Unrecovered cellulose & hemicellulose	0.13	kg	0.07	kg
Energy from unrecovered cellulose & hemicelluloses	1.9	MJ	1.1	MJ
Total Potential Energy for Plant Use	**8.3**	**MJ**	**7.5**	**MJ**

Source: Isci 2008, Badger 2002

Note: grayed cells indicate key parameters in scenario modeling.

* On average, each kilogram of switchgrass contains 42% cellulose, 31% hemicellulose, and 28% lignins, along with small amounts of ash (Isci 2008).

**Midpoint heating value of 23 MJ/kg lignin, based on natural range of 20.9-25.5 MJ/kg (Ligninbiofuels 2008)

In the High scenario, enzyme and bacteria improvements are assumed to result in an increase in fermentation efficiency to 90% for glucose and 70% for xylose. The increased cellulose and hemicellulose recovery ratios, combined with higher fermentation efficiencies, results in a lower volume of residues and higher emissions of CO_2, as a greater proportion of the feedstock is converted to alcohol.

The lignin content of switchgrass is not subject to hydrolysis and fermentation and is assumed in most descriptions of cellulosic ethanol plants to be recovered, dried, and combusted to provide process energy and electricity generation. In the two cases examined here, the unrecovered cellulose and hemicellulose is treated as part of the recycled lignin fraction. The remaining unrecovered mass from the initial kilogram of switchgrass includes the balance left from incomplete fermentation as well as the small amount of the sugars taken up by the growth of the fermenting agent yeast or bacteria. Because of the dilute nature of this remaining fraction, it is assumed that it is disposed of through the water treatment facilities and that energy is not expended for recovery.

Based on a 27 MJ/l output total-plant energy requirement, one implication of this mass balance is that switchgrass ethanol plants will not be self-sufficient in process energy derived from their feedstock and will require external energy purchases. In the Average case, the lower recovery factors result in a higher volume of lignin and cellulosic residue for combustion, but as efficiency rises and ethanol yield increases, even less cellulosic mass remains to supplement the potential energy from lignin. In the average case, the 0.24 liters of ethanol produced from the 1 kg of switchgrass requires 6.6 MJ (0.24 l x 27 MJ/l) of energy compared to the potential recovery of 8.3 MJ from the switchgrass, but this potential energy does not take into account combustion losses or electricity generation losses. In addition, it is unclear from the literature if the energy needed to dry the lignin and cellulose fractions is included within the estimated 27 MJ/l total plant requirement. The gap between energy consumption and the potential yield from lignin and cellulosic fractions increases as the yield rises: in the High case, the production of 0.35 l of ethanol requires 9.3 MJ of energy, compared to the potential remainder of 7.5 MJ from lignin and cellulosic fractions prior to combustion, and prior to conversion losses. In the latter case, the nominal gap is equivalent to about 0.5 kWh per liter.

2.6. Transportation and Distribution

Two major transportation requirements exist: to move the harvested switchgrass from the fields to the biorefinery and the finished ethanol from the plant to the distribution terminal for blending. This analysis does not look beyond the distribution terminal to point-of-sale distribution of the final product, because this activity takes place regardless of the availability of ethanol blending components.

Dried switchgrass has a lower density than hay but grows taller. Demonstrations in Iowa and Kansas have shown that switchgrass can be mowed, raked, and baled using the same equipment as used for baling hay, although the taller grass sometimes will create jams in the baling equipment (Popp 2007, Duffy 2001). Because the switchgrass harvest will be destined for industrial use and not as animal feed, it is assumed that large bales (3 ft x 3ft x 8ft bales of about 600 pounds weight, or "one ton" bales of about 1700 pounds weight) will be the preferred form for bulk transportation. Switchgrass transport will likely rely on the existing fleet of semi-flatbed trucks, which, for example, currently account for half of total hay transport in the state of Washington (Meenach et al. 2004) (Figure 5).

Figure 5. Semi-flatbed Transport of Baled Hay

Source: Pleasant Hills Farms, www.pleasanthillfarmsllc.com

The energy requirement for transporting the switchgrass bales from field to biorefinery was calculated based on the tonne-kilometer intensity of this type of diesel-fueled heavy vehicle, assuming a 15 tonne tare weight (i.e., the weight of an empty vehicle) and a 17 tonne load for a gross weight of 32 tonnes, requiring 2.0 MJ/t-km (3,100 BTU/ton-mile) in energy consumption (EIA 1995, WZI 2008).

The average distance that switchgrass is transported from field to biorefinery differs by biorefinery based on the allocation optimization described in section 2.4. The total fuel consumption for delivering switchgrass also takes into account a return trip with empty flatbed of equal distance as the delivery.

Each biorefinery would, on average, require the delivery of 100 to 110 truck-loads of switchgrass per day. Because switchgrass is harvested only once or twice a year—with a single harvest after fall senescence resulting in the lowest loss of nutrients--deliveries would be highly seasonal and likely concentrated in the fall and early winter months. The implication of seasonal delivery is the requirement for large areas of biomass storage at the biorefinery. In this study, it is assumed that the loss rate for biomass storage is 7 percent (Williams 2008), though other studies estimate it to be 1 percent per month (Epplin et al. 2007).

In California, ethanol is "splash-blended" with unfinished gasoline into fuel delivery trucks at time of loading at the bulk petroleum distribution terminals throughout the state. Currently, California has about 42 fuel terminals, mostly located near the coast in San Diego, Los Angeles and Orange Counties, the San Francisco Bay Area, and Eureka. Inland terminals are located around major population centers such as Sacramento, Stockton, Tracy, Chico and Bakersfield. In this study, it was assumed that liquid fuel tanker trucks would deliver ethanol from the biorefinery to the closest fuel distribution terminal, traveling an average distance of 68 miles one way and returning empty the same distance. The distance from the biorefinery to terminal was determined by clumping the multiple terminals in those counties where they exist (e.g. Los Angeles County) to a single location in the middle of the county as the point of measurement from the biorefinery (see Section 2.4 for discussion of the siting of biorefineries).

The ethanol transport trucks are assumed to be identical to standard diesel-fueled gasoline transport trucks, carrying 9,000 gallons of fuel with a cargo weight of 27 tonnes in addition to the 15-tonne tare weight of the tanker truck (Unnasch et al. 2007). The energy intensity of transport is the same as the semi-flatbed for switchgrass transportation at 2.0 MJ/t-km (3100 BTU/ton-mile), and total energy consumption includes both delivery and return.

3.0 Project Results

3.1. Switchgrass and Ethanol Production

The results of the model calculation of switchgrass planting potential based on displaced irrigated pasture acreage and water availability not surprisingly show a concentration of production in the Central Valley counties and in the irrigated lands of Southern California (Figure 6). In total, about 1.1 million hectares (2.7 million acres) were planted in switchgrass.

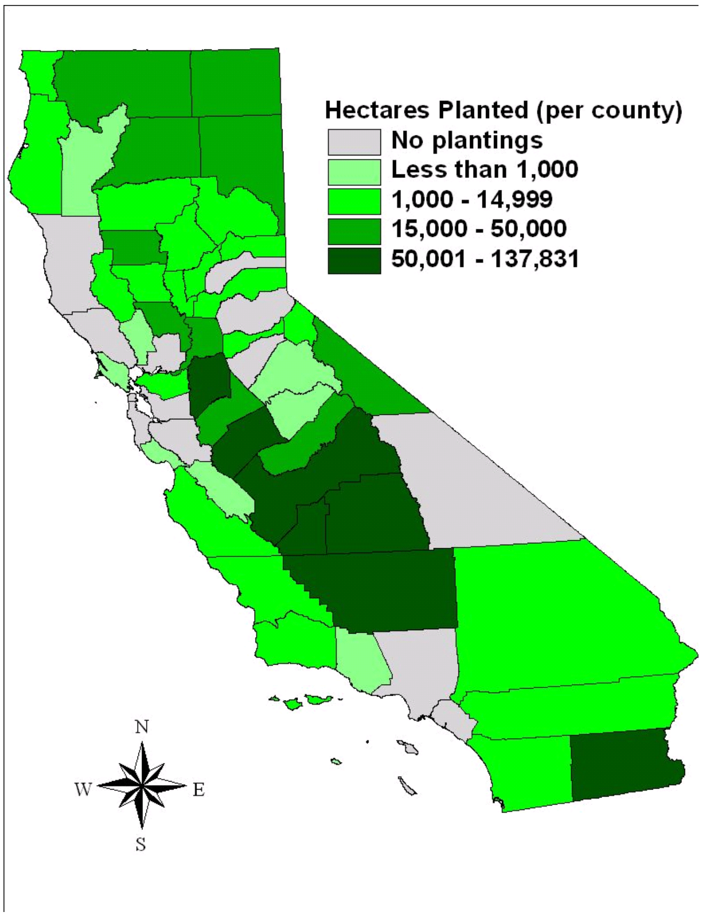

Figure 6. Distribution of Switchgrass Planting

Source: Lawrence Berkeley National Laboratory

The number of biorefineries established within economic distance of switchgrass producers increased as the assumed yield per hectare grew (Table 3 to Table 6, High Case biorefinery efficiency only). In the case of the lowest yield per hectare—7 tonnes/hectare—a total of nine biorefineries were needed to accommodate total output, the unallocated balance being too far to transport and insufficient in volume to support a 50 MGal/year biorefinery. A cluster of four biorefineries were located in Fresno County, where the distance to a biorefinery averaged 144 km (89 miles) in mass-weighted distance terms. In some cases, such as the biorefinery located in Siskiyou County, the longer average distance reflects the transport of switchgrass from neighboring counties, the volume produced in Siskiyou alone being insufficient to support a biorefinery of the assumed scale.

Table 3. Switchgrass Allocation and Biorefineries, 7 t/ha Yield, High Case Efficiency

County	Total County Production ('000 tonnes)	Number of Plants	Allocated Production ('000 tonnes)	Unallocated Balance ('000 tonnes)	Avg. Distance to Biorefinery (km)
Fresno	868	4	868	-	144
Imperial	827	1	596	231	122
Kern	713	1	596	117	82
Plumas	58	1	58	-	84
Siskiyou	276	1	258	18	130
Stanislaus	276	1	276	-	69
All	6,829	9	5,360	1,469	118

Source: Lawrence Berkeley National Laboratory

Table 4. Switchgrass Allocation and Biorefineries, 9 t/ha Yield, High Case Efficiency

County	Total County Production ('000 tonnes)	Number of Plants	Allocated Production ('000 tonnes)	Unallocated Balance ('000 tonnes)	Avg. Distance to Biorefinery (km)
Amador	10	1	10	-	51
Butte	46	1	46	-	37
Fresno	1,116	1	1,113	4	144
Imperial	1,063	1	596	468	122
Kern	917	1	596	321	82
Kings	663	1	596	67	116
Merced	656	3	656	0	73
Siskiyou	355	2	348	7	130
Tulare	614	1	596	18	146
All	8,780	12	7,147	1,633	98

Source: Lawrence Berkeley National Laboratory

Table 5. Switchgrass Allocation and Biorefineries, 11 t/ha Yield, High Case Efficiency

County	Total County Production ('000 tonnes)	Number of Plants	Allocated Production ('000 tonnes)	Unallocated Balance ('000 tonnes)	Avg. Distance To Biorefinery (km)
Calaveras	-	2	-	-	63
Colusa	73	1	73	-	60
Fresno	1,365	4	1,365	0	144
Imperial	1,300	2	1,191	108	122
Kern	1,120	1	1,120	0	82
Kings	810	1	810	-	116
Merced	802	1	802	-	73
Modoc	433	2	433	-	182
San Luis Obispo	32	1	32	-	137
Tulare	750	1	750	-	146
All	10,731	16	9,529	1,202	120

Source: Lawrence Berkeley National Laboratory

Table 6. Switchgrass Allocation and Biorefineries, 13.5 t/ha Yield, High Case Efficiency

County	Total County Production ('000 tonnes)	Number of Plants	Allocated Production ('000 tonnes)	Unallocated Balance ('000 tonnes)	Avg. Distance to Biorefinery (km)
Fresno	1,675	2	1,675	0	144
Imperial	1,595	2	1,191	404	122
Kern	1,375	2	1,375	0	82
Kings	994	1	943	51	116
Merced	984	4	984	0	73
Monterey	26	1	26	-	89
San Joaquin	637	1	596	42	
Siskiyou	532	3	515	17	130
Sutter	84	2	84	-	51
Tulare	921	1	596	325	146
All	13,170	19	11,316	1,854	96

Source: Lawrence Berkeley National Laboratory

For each yield scenario, the location of biorefineries is optimized for that scenario, based on the minimization of unused material and minimal transportation distance. The major producing counties such as Fresno appear in each scenario, but smaller producers such as Amador, Butte, or even Calaveras county were no production is recorded, appear based on the volume of production in neighboring counties and their locations based on the minimization calculations. Total transport turnover doubles between the low yield, average efficiency case and the high yield, high efficiency case, from about 500 million tonne-km per year to over 1 billion tonne-km per year (Table 7).

Table 7. Summary of Biorefineries and Crop Requirements, all cases

Scenario	Total Number of Biorefineries	Biorefineries in N. California	Biorefineries in S. California	Biorefinery Crop Requirement ('000 tonnes)	Total Crop Transport Turnover ('000 tonne-km/yr)
7 t/ha; avg. efficiency	7	1	6	4,731	522,772
7 t/ha; high efficiency	9	2	7	5,335	618,554
9 t/ha; avg. efficiency	11	3	8	7,434	853,494
9 t/ha; high efficiency	12	4	8	7,113	655,268
11 t/ha; avg. efficiency	14	4	10	9,462	878,318
11 t/ha; high efficiency	16	3	13	9,485	899,931
13.5 t/ha; avg. efficiency	17	5	12	11,489	1,045,419
13.5 t/ha; high efficiency	19	5	14	11,263	1,037,972

Source: Lawrence Berkeley National Laboratory

Production of ethanol under each of the scenarios varies from 182 million gallons of gasoline equivalent (ethanol containing 65% of the energy of gasoline) in the average efficiency case with low per-hectare switchgrass yields to 618 million gallons gasoline equivalent in the high efficiency, high per-hectare yield case (Table 8). Compared to total California gasoline consumption of 15.67 billion gallons in 2007 (Board of Equalization 2008), this represents only a 1.2% to 4.0% potential for substitution.

Table 8. Ethanol Production Under All Scenarios

Parameters		Ethanol Production		
Yield	Efficiency	Ethanol (mill. gals)	Gasoline-Equivalent (mill. gals)	% Calif. 2007 Gasoline Consumption
7	Average	280	184	1.2%
7	High	450	295	1.9%
9	Average	440	289	1.8%
9	High	600	393	2.5%
11	Average	560	367	2.3%
11	High	800	525	3.3%
13.5	Average	680	446	2.8%
13.5	High	950	623	4.0%

Source: Lawrence Berkeley National Laboratory

3.2. Energy and Water Consumption

Table 9 summarizes, for each scenario, the total energy content of the ethanol produced state-wide and the major components of the energy used in production. The recycled biomass includes both the recovered lignin and the cellulose and hemicelluloses fractions that remain unrecovered after initial processing. The table also shows the fraction of energy use supplied by recycled material, which is 56-57% at with high recovery and fermentation efficiencies and 87-88% at average efficiency. The transportation energy includes the amount of diesel fuel used trucking feedstock to the biorefinery and the amount used trucking ethanol to the distribution points. The sum of the recycled biomass, purchased and transport columns provides a lower bound on the total energy inputs for ethanol production. For these numbers, the transportation component is 7-11% of the total.

This table allows the calculation of various energy return measures. "Energy return on investment", or the amount of energy acquired compared to the amount of energy expended to acquire it, is about 0.7-0.73 with weak variation across scenarios, showing a net loss. (Energy return on investment is distinct from conversion efficiency, which is always less than 100% and measures the ratio between the input energy source and the useful energy derived from it on conversion, such as power generation or petroleum refining[7]). The low energy return is dominated by the high level of plant processing energy, which can be reduced as improvements in preprocessing and other conversion steps are made. The ratio of ethanol energy output to total external energy (purchased plus transport) is approximately 5-6 at average efficiency and

[7] For a fuller discussion of the concept, see, for example Cleveland et al. 2000.

1.6-1.7 at high efficiency, with only weak variation with yield. It is important to interpret these numbers correctly. If the purchased energy is or can be a substitute for transportation fuel, then in the average efficiency scenario spending 1 unit of useful energy produces 5-6 units of useful energy, for a net gain of 4-5. In the high efficiency case, spending 1 unit produces 1.6-1.7 units for a net gain of 0.6-0.7. An economic analysis of the benefits of investing heavily in cellulosic ethanol production should consider these measures of net energy gain.

Table 9. Ethanol Output and Energy Use

Parameters		Energy Output (PJ)	Energy Used in Production and Transportation (PJ)			Recycled Biomass*	
Yield	Efficiency	Ethanol	Plant Fuel	of which: Purchased Fuel	Transportation Fuel (Diesel)	PJ	% Energy Use
7	Average	22	29	1	3.4	28	87%
7	High	36	46	18	4.1	28	56%
9	Average	35	45	1	5.4	43	86%
9	High	48	61	24	4.4	37	56%
11	Average	45	57	2	5.7	55	88%
11	High	64	82	32	4.9	50	57%
13.5	Average	54	69	2	6.7	67	88%
13.5	High	76	97	38	7.0	59	57%

*Includes lignin and unrecovered cellulosic fractions inside the biorefinery

Source: Lawrence Berkeley National Laboratory

Water use and the associated energy consumption at the biorefinery have also been estimated. Table 10 shows the estimated water use and associated energy. Conveyance energy for water used within the biorefinery is calculated from average values (in units of MJ/l) for northern and southern California (Klein 2005) based on the location of the biorefinery. The average energy consumption for wastewater treatment was estimated at twice the value for residential wastewater (for residential the number is 2378 MJ/Ml) (Klein 2005) in the absence of more complete information.

Total water use is estimated based on two steps in the process: separation by dilute acid hydrolysis (DAH) and distillation. DAH is not the only possible method to use in this step, but is taken as the example process here because it is a proven method for processing cellulose, and because there is some data available on the required inputs. No public information is currently available on the details of DAH processes for switchgrass, so the estimate here is based on process data for conversion of sugarcane biogases (BJCE 1997). In that example, approximate 10 liters of water is used per kg of dry matter. It is assumed that the DAH wastewater is not reused in distillation, as it will contain acids and possibly other reactive agents. The water requirement for distillation is approximately 25 liters per liter of ethanol output, assuming a concentration of 4% ethanol by volume after the fermentation stage (USDA 2006). This leads to a total water requirement per biorefinery of 66 liters per liter of ethanol out for average and 53 liters per liter of ethanol out for high efficiency. At high efficiency, water use intensity is lower because less dry matter is needed to produce a liter of output, but total water use is somewhat higher because output is higher. Total water use also varies with yield due to varying total output.

The energy required for conveyance and waste-water treatment is approximately 20-25% of the energy needed for transportation. These numbers are specific to California as conveyance of water to the southern part of the state is energy-intensive. This energy is used by the water and wastewater utilities that supply the biorefinery, not within the plant itself (unless it is designed to process its own wastewater) and has not been included in Table 9. It can be thought of as an externalized resource cost, i.e., a resource cost imposed on the state as a whole by the ethanol industry.

Table 10. Statewide Total Water Use and Associated Energy Use by Scenario

Yield	Efficiency	Total water use Ml/yr	Energy for conveyance TJ/yr	Energy for treatment TJ/yr	Total Energy TJ/yr
7	Average	69,649	507	166	672
7	High	90,739	600	216	816
9	Average	109,448	678	260	938
9	High	120,985	689	288	976
11	Average	139,298	848	331	1,179
11	High	161,314	1,114	384	1,497
13.5	Average	169,147	1,018	402	1,420
13.5	High	191,560	1,202	456	1,658

Source: Lawrence Berkeley National Laboratory

3.3. Impact of Potential Efficiency Improvements

Detailed results have been presented above for two process efficiency scenarios, average and high. This section presents a more general examination of the required inputs and ethanol output as a function of the efficiency parameters. It will be shown that, assuming the 28 MJ/l energy requirement for the biorefinery as a whole does not vary with process efficiency, the additional energy input exceeds the energy content of the additional output as the biorefinery efficiency increases.

The various components of a kg of input switchgrass can be represented as

$1 = C + H + L + A$

where

- C is the mass fraction of cellulose
- H is the mass fraction of hemicellulose
- L is the mass fraction of lignin
- A is the mass fraction of ash

The cellulose and hemicellulose undergo somewhat different processing, with differing values for the process efficiencies. We define these efficiencies as follows:

- XCR is the recovery efficiency for cellulose
- XCF is the fermentation efficiency for cellulose
- XHR is the recovery efficiency for hemicellulose
- XHF is the fermentation efficiency for hemicellulose

The efficiencies XCF and XHF defined above represent the fraction of material that will successfully undergo fermentation. In the chemical conversion of sugars to ethanol and CO_2, the chemical formulae for these constituents also define a *stoichiometric efficiency*—the mass fractions based on chemical composition-- XS, which is equal to 0.51 (Badger 2002)

The recovery efficiencies are applied to the H and C mass fractions. From the original kg of input dry matter, the quantity that continues to the fermentation process is

M1 = XCR*C + XHR*H

By mass conservation, the remaining mass is

R1 = (1-XCR)*C + (1 – XHR)*H

The quantity of material R1 can theoretically be added to the lignin fraction L and used as a fuel source. This material will be recovered in an acid solution, and so must be neutralized and dried before it can be burned. The mass R1 decreases as recovery efficiencies increase.

The mass of ethanol is obtained by applying the fermentation and stoichiometric efficiencies to the material content of M1:

M2 = XS*(XCF*XCR*C + XHF*XHR*H)

The mass M2 is mixed into a dilute solution which is then distilled and dehydrated to produce the final ethanol product.

The CO2 byproduct from fermentation is

MCO2 = (1 - XS)* (XCF*XCR*C + XHF*XHR*H),

and the remaining mass is

R2 = (1 – XCF)* XCR*C + (1 – XHF)*XHR*H.

The mass R2 contains dilute fermentation byproducts and presumably must be disposed of as waste. The reader can confirm the mass balance relations

M1 + R1 = C + H

M2 + MCO2 + R2 = M1

As efficiencies vary, the primary quantities of interest are the output ethanol M2 and the available fuel L+R1. These quantities have been calculated for a range of efficiencies defined by $0.75 \leq XRC \leq 0.95$, $0.75 \leq XFC \leq 0.95$, $XRH = 0.9$, $0.5 \leq XFH \leq 0.7$.

As the output M2 varies with increasing efficiency, the total energy required by the plant goes up and the amount of recycled material available as fuel goes down. This means that, as efficiencies increase, the difference between the energy required and the energy that can be obtained internally increases. This external energy or *energy deficit* must be made up from outside the plant, and thus represents the marginal external resource cost of improved efficiency.

Figure 7 shows the energy deficit plotted against the ethanol output per unit of input for the grid of efficiency values defined above. The energy deficit is calculated using an energy content for lignin of 23 MJ/kg, for cellulose of 14.5 MJ/kg, and assuming this material is burned in a boiler system with efficiency of 0.8. On the horizontal axis, the output ethanol is converted to equivalent energy using the lower heating value (LHV) of 21.1 MJ/l (TEDB 2007). The plot also shows the estimated energy required to dry the fuel. It is unclear from the existing literature whether this energy is included in the 27 MJ/l figure or not. If it is not, it should be added to the energy deficit.

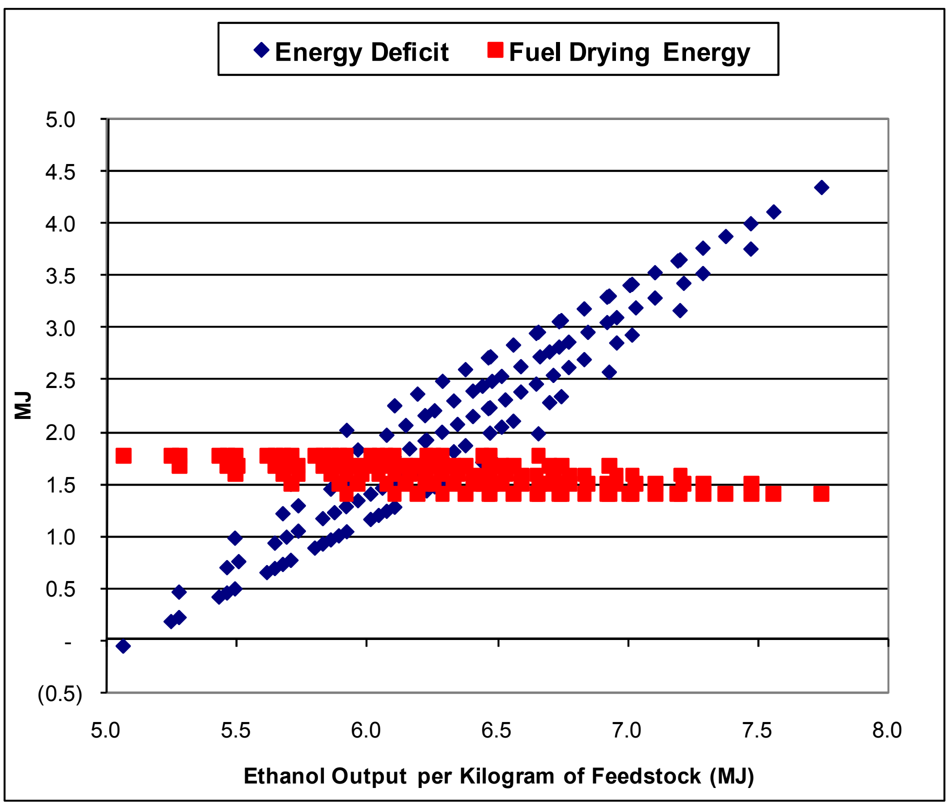

Figure 7. Energy deficit in MJ plotted against ethanol output in MJ per kilogram of switchgrass feedstock. The plot shows values calculated for a set of varying process efficiencies.

Source: Lawrence Berkeley National Laboratory

This plot illustrates two very important points. First, under the lowest efficiencies included in the set of calculations, which correspond to current average conditions, the energy balance is essentially break-even, but at higher recovery and fermentation efficiencies, the deficit becomes increasingly positive. This means that energy is required from outside the biorefinery to produce ethanol. Numerous authors (using the equivalent of the "high" efficiency parameters as this study) have claimed that cellulosic biorefineries can be energetically self-sufficient and even electricity exporters, but none has ever provided the quantitative analysis, or even a coherent explanation, of how this would be achieved. The analysis presented here is transparent and based entirely on simple physical principles. It shows that cellulosic ethanol production, under a wide range of potential future intensity improvements, requires external energy inputs. These results are consistent with Patzek & Pimentel (2004) who are the only authors to provide detailed information on fuel inputs.

The second point illustrated by this graph is that, as efficiency improves, the required external energy (i.e., the increase in the energy deficit) increases more rapidly than the energy content of the output ethanol. Equivalently, the slope of the set of squares in

Figure 7 is greater than one. This implies that investments that aim at increasing the recovery and fermentation efficiencies of the biorefinery should be considered very carefully. Given these results, if the external energy source (electricity, natural gas, etc.) is an effective substitute for transportation fuel, then there is no net gain associated with improving recovery and fermentation efficiencies. The additional energy used to produce more ethanol could directly provide more transportation services than the additional ethanol.

Although this analysis is simplified, the conclusions are unlikely to change as more detail is added. The estimates of recyclable fuel are maximum values, and likely to be optimistic. Other considerations, such as controls on emissions from burning biomass, would further reduce the net energy available from recycled biomass. If cellulosic ethanol production is to be energetically viable, it may be more important to focus on the processing energy consumption than to improve the efficiencies of the biochemical processes involved.

3.4. Economic Considerations

This section provides a concise examination of economic constraints on cellulosic ethanol production in California. The key relationship is that between the price paid to farmers for the switchgrass feedstock and the price at which ethanol can be sold in the market.

A farmer possesses fixed capital consisting of land and access to water, and will use this capital to maximize profit (more or less) within limits imposed by the difficulty of switching crops. While the value per unit of output, and the output per acre of land, can differ substantially between crop types, in general one expects the return on capital to be comparable to a state-wide average for a given crop category. The return on capital can be approximated by the value per acre obtained from crop production. The crop category relevant to switchgrass is field crops (grasses and grains).

Agricultural census data for California (USDA 2007) provides the acres planted, output and value obtained by county and by commodity (or crop type). For these data, values were generalized to crop categories by aggregating based on the first three digits of the commodity code, then summing over all counties that produce the crop. This allows an estimate of the value per acre associated with different types of crops. As expected, comparable crops (in this case, grain, silage, hay etc.) show comparable values, with a median of about $300/acre in 2008 dollars, or $750/Ha. This represents a *minimal* value that must be paid to farmers to induce them to grow switchgrass.

The relationship between the switchgrass price and the ethanol price is summarized in the formula

[F + CR + OC]*(1 + M) = PE

where

- F = cost of feedstock ($ per gallon of ethanol)
- CR = capital recovery cost of ethanol plant ($ per gallon of ethanol)
- OC = operating cost ($ per gallon of ethanol)
- M = markup on the finished product (dimensionless)
- PE = ethanol price ($ per gallon)

Dividing through by PE gives

[F/PE + CR/PE + OC/PE]*(1 + M) = 1

Based on Tiffany (2005), for corn ethanol plants CR/PE is about 0.1 and for cellulosic ethanol it is expected to be 0.3. For corn ethanol OC/PE is about 0.35 with energy costs about 15% of this component in 2005. As cellulosic ethanol requires about twice as much energy per unit of output, OC/PE for cellulosic would be 0.40 at a minimum. The markup M (which includes taxes, marketing, and profits) should be the same for both products as it reflects costs downstream of the biorefinery. The price PE must also be the same for both products as they are sold into the same market.

That means that, to compete with corn ethanol, F/PE for cellulosic ethanol can be at most equal to (1-0.4-0.3) = 0.3, i.e. the feedstock cannot be more than 30% of the selling price of ethanol. The current rack or wholesale price for ethanol is $2.59/gallon[8]. Based on an F/PE of 0.3, the implied price per tonne of switchgrass and corresponding value per acre can be calculated for the yields and efficiency scenarios discussed above. The results are presented in Table 11. These should be compared to the current estimate of $750/Ha for field crops. For most of the scenarios, the implication is that a farmer selling switchgrass to an ethanol plant would earn less per hectare

[8] April 2008 rack price, Nebraska, as reported monthly at http://www.neo.ne.gov/statshtml/66.html

than they would growing wheat or hay. On the other hand, if the farmer is paid a competitive price, cellulosic ethanol (under current conditions) would not be competitively priced.

Table 11. Implied Value in $/ha that a farmer would earn selling switchgrass feedstock

Yield t/ha	Average Efficiency	High Efficiency
7	322	459
9	414	590
11	506	721
13.5	621	885

Source: Lawrence Berkeley National Laboratory

4.0 Conclusions and Recommendations

The goal of this project was to test the feasibility of using a physically-based approach to assess alternative energy production options for California. One strength of this approach is avoiding the problems of economic-based analysis in an era characterized by large jumps in the costs of basic inputs such as energy and raw materials, and very high uncertainty over the path of these costs into the future. At the same time, the approach can credibly estimate the magnitude of potential production and associated energy and resource requirements, and highlight potential bottlenecks or other challenges to implementation. Moreover, from a physical point of view, the analysis is transparent and parameterization of the key uncertainties allows testing of the impact of alternative assumptions on resource consumption, yields, and net energy gains.

The research team chose to focus on the case of cellulosic ethanol production because of the widespread expectation that it will be the next-generation biofuel to replace corn ethanol, and is increasingly the focus of much academic, scientific and corporate research. The findings of this research project call into question many assumptions about the viability of cellulosic ethanol, based on the following issues:

1. Water is a critical constraint to the development of a large-scale cellulosic ethanol industry in California. The Mediterranean climate of California requires irrigation of summer-growing crops, and water must be obtained either by changes in crop selection on currently irrigated cropland, or though purchase at prices in competition with urban water districts. For any cellulosic crop to provide enough feedstock to affect the supply of liquid fuels in California, millions of acres of irrigated land—and the associated water—will be required. With future water supplies under threat from global warming, it is not certain how these water demands could be met.

2. Cellulosic ethanol plants, under current and foreseen technology conditions, cannot be energy self-sufficient or exporters of electricity, despite widespread claims to the contrary. The imposition of mass conservation requirements on a cellulosic ethanol plant as outlined in this project shows that the supply of recycled lignin and cellulosic fractions is insufficient to provide all plant process energy, in some cases providing only one-half of what is necessary. The remainder must be purchased as external energy. To the extent that the purchased energy is a substitute for transport fuels, any gain in ethanol production is offset by the increased need for external energy. If this energy is supplied by fossil fuels some of the expected carbon savings from cellulosic ethanol production will also be lost. The air quality impacts of burning biomass are still poorly understood and may impose additional limitations on the use of this fuel source.

3. The assumptions used here—the complete diversion of all irrigated pasture and fiber-crop land to switchgrass production—resulted in total output of only 1.2-4.1% of California's gasoline requirement, less than the current blending mandate.

4. Improving recovery and fermentation efficiencies to get higher ethanol yields per unit of input appears to result in decreasing marginal benefits, as higher amounts of purchased energy are required for production of higher yields. These results suggest, at the very

least, that improving the biorefinery design to substantially lower the energy requirements is essential if cellulosic ethanol is to be a viable liquid fuel.

5. Achieving the high yields (13.5 tonnes/ha) as assumed in many studies will require more intensive agriculture. Although switchgrass is touted as growing on "poor, marginal land", yields from marginal lands are, at best, marginal. High-volume industrial-level switchgrass production is management and agriculture resource intensive, and thus will create competition between fuel crops and food (human or animal) crops. In an era of growing concern over food prices and global food availability, this competition needs to be seriously considered.

6. A farmer's decision to grow switchgrass or other crops on a fixed amount of land depends in part on the expected revenue per acre that will be obtained from this activity. The price a farmer obtains for switchgrass must be competitive with what they receive for comparable (hay or forage) crops. The amount that can be paid to farmers depends in turn on the price of ethanol. Under current prices, at high yield levels and high plant efficiencies this economic balance is feasible, but at low yields or low plant efficiency the price required by farmers is too high relative to the price of ethanol. As noted above, however, at high plant efficiency the energy balance of ethanol production is not favorable. Overall, these results imply that switchgrass-based ethanol is not likely to be both cheap and plentiful.

One challenge to the implementation of this project was the general lack of in-depth information about the internal operations of cellulosic ethanol plants, in contrast to the wealth of data about the energy and cost conditions in a corn-based ethanol plant. Few cellulosic plants exist and none on a commercial scale and much of the detailed energy and operations data from research or pilot projects have been kept proprietary. This is a serious impediment to the realistic evaluation of the benefits of allocating public funds to research into cellulosic ethanol production. It is recommended that, if California provides any public funding for cellulosic ethanol demonstration plants, requirements be put in place to make basic operating parameters of such plants public, or at least available to other state-supported researchers.

This study has demonstrated the value to California of using a physically-based approach to the evaluation of alternative energy projects. Although development of the methodology is still in an early phase, it is evident to the research team that such an approach can be applied to other large-scale alternative energy projects, for example solar PV, solar thermal projects or "clean coal". To the extent that constraints on the viability of large-scale infrastructure development are not just financial, this approach can provide very valuable insights that are not sensitive to highly uncertain economic variables. The methodology can apply equally well to demand-side conservation measures. To further improve the methodology, extend the boundaries of coverage to other economic sectors, and expand the scope of the policy scenarios that can be considered, further research funding would be needed.

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Appendix A: Foodwebs and Energy Accounting

This section explains the ideas behind foodweb modeling in more detail and presents a simple example of the mathematical formulation of a model. It also describes how the foodweb concept can be applied to physical energy production and consumption in the economy, and why this approach can help resolve difficulties that arise when trying to analyze large scale changes to the productive economy.

Basic Foodwebs

An ecosystem consists of a set of organisms in a particular region together with the surrounding physical environment, that form a coherent, relatively stable assemblage of populations. Members of an ecosystem interact and are mutually dependent in a wide variety of ways, but perhaps the most basic is that they eat, and are eaten by, one another. *Food web* is the term used to describe the network of relationships defined by who eats whom (trophic web is a more technical term that means the same thing). Many people are familiar with the notion of a *food chain*, which describes a hierarchy of organisms, each of which can eat the one below it in the chain. For example the trio (flies, fish, bears) is a simple food chain; bears eat fish and fish eat flies. In reality, fish eat many things besides flies, and flies are eaten by many organisms which are not fish. A food web is a more complete representation of the way various members of an ecosystem act as food sources for one another. Biologically, food is important because it is a source of energy, so a foodweb can also be thought of as a map of the energy and material flow through an ecosystem. It is this more abstract view that will be used to develop a comparable model of the economy. In order to be complete, a foodweb model must include some representation of how energy enters the ecosystem, and of how waste products or detritus are processed.

It is intuitively clear that the relative populations of different species coexisting in an ecosystem are not arbitrary, and must be related to the availability of food. To use an economic term, one can say that to maintain an ecosystem nature must solve an allocation problem, partitioning land, water and biomass resources among each member of the assemblage. A solution to this allocation problem is a situation where the proportions of different species are such that the ecosystem can reproduce itself year-to-year in a stable manner.

To build a quantitative model, some simplification is required. The approach taken by foodweb analysis (Post 2002, Drossell & McKane 2003) is to define categories of organisms based on what they eat and what they are eaten by. These categories are known as *trophic levels*, and are ordered (like the elements of a food chain) from a basal level to a top level. The basic structuring rule is that a species at a given trophic level does not eat anything from any level above it. Species within the same level may consume one another (this is known as *autotrophy*), and a species may also consume organisms from multiple levels below it (this is known as *omnivory*) . The lowest level of the web consists of primary producers, which are either photo-synthesizers or creatures that feed on detritus. The top level consists of species with no predators, for example large mammals.

In a mathematical foodweb model, the dependent variables are the total biomass for each species. Changes in biomass can be due to a change in the number of individuals and/or a change in the typical size of an individual, with the latter being an important indicator of species health. The models can be formulated as ordinary differential equations describing the continuous rate of change of biomass, or as algebraic equations using a discrete time variable (for example an annual time step).

The broadest categories that can be used to define a trophic level are producers, herbivores, carnivores and omnivores. The producers sit at the base of the food web, and include plants and micro-organisms. A number of environmental conditions affect the productivity of organisms at this level, particularly the availability of water and soil nutrient levels. Modeling these factors may require an explicit description of spatial variation in the environment. At the next level, herbivores eat only plant material and may be integrated into plant reproductive systems. Carnivores are loosely thought of as the "top of the food chain", and eat only other animals. This category includes both large predators such as lions, and many insect species such as mosquitoes and spiders. Humans belong to the omnivores, which consume both plants and other animals.

In ecological applications, these general categories are broken down further into more specifically defined levels that reflect the principal interactions in a given ecosystem (Schoener 1989). The number of levels, and groups within a level, to include in the model depends both on the system itself and the purpose of the model. Any specific model will be approximate, as it may not be possible to include all interactions or to order all species in a strict consumption hierarchy. However, imposing some structure on the system makes it much more tractable to analyze.

The equations used to describe a foodweb are derived from the assumption that population growth for a given species depends primarily on (1) the current size of the population and (2) the size of the available food supply. The first assumption is ubiquitous in population modeling. The second assumption highlights the role that food (and implicitly energy) plays in population growth. These two assumptions, together with the physical requirement of conservation of mass, are sufficient to develop a set of equations describing the evolution of each of the member species of a foodweb.

These concepts are illustrated below in a simple model adapted from Thebault & Loreau (2003). The describe a model with three trophic levels: producers $\mathbf{P_i}$ (level 1), herbivores $\mathbf{H_i}$ (level 2) and carnivores $\mathbf{C_i}$ (level 3). Carnivores eat only herbivores and herbivores eat only producers. The index **i** denotes a particular species within the given trophic level. The index **n** represents a time step which is here defined to be one year (many organisms reproduce annually).

Each equation gives the total mass of organism in time step **n+1** as a function of the mass available in time step **n**. For carnivores:

$$C_i(n+1) = C_i(n) - a_i C_i(n) + \Sigma_j \left(U_{ji} * H_j(n) \right) * C_i(n). \quad (1)$$

The growth of the carnivore population depends directly on the availability of its food source, the herbivore population **H_j**. The coefficient **U_{ji}** captures the "conversion efficiency" of herbivore biomass to carnivore biomass. The term in **a_i** represents the mortality rate. For the herbivores,

$$H_i(n+1) = H_i(n) - b_i * H_i(n) + \Sigma_j (- U_{ij} * C_j(n) + V_{ji} * P_j(n)) * H_i(n). \qquad (2)$$

This equation includes terms representing the loss of herbivore mass due to mortality, the loss due to predation by carnivores, and the gain which depends on consumption of producers. The model imposes mass conservation: the loss of herbivore mass in equation (2) is balanced by gains in equation (1).

At the producer level, the equation is

$$P_i(n+1) = P_i(n) + \Sigma_j (- V_{ij} * H_j(n)) * P_i(n) + c_i * P_i - d_i (P_i(n))^2. \qquad (3)$$

It includes a term to account for losses to herbivores (which balances the gain in equation (2)), a natural growth term proportional to the coefficient **c_i**, and a nonlinear term that represents in a mathematically simple way the finite carrying capacity of the environment. If appropriate, equation (3) could also include detritus terms representing the return of the physical remains of carnivores and herbivores to the ecosystem.

Application to Energy Accounting

In the economy, the analogue of predator-prey relationships is consumption-production relations, with the human consumer as top predator. To mimic the trophic web structure, the economy must be represented such that inputs to production at a given level come only from lower levels in the system**.** The core assumptions of foodweb models, that growth depends on the current size of the population and the availability of needed inputs, are intuitively reasonable and consistent with data on the relationship between economic variables such as GDP, and population and energy use. In contrast to standard economic models, this approach highlights the role that the physical supply of various inputs plays in maintaining growth. It can therefore provide a much simpler, more transparent framework for the study of the effect of supply constraints or large shifts in primary resource use. Accounting for waste products, pollutants and resource depletion is also much more straightforward in this type of model.

The foodweb approach does not ask *why* the economy grows: within this framework growth is a spontaneous response to favorable environmental conditions. On the other hand, within this system lack of growth is not defined as pathological. A stable or low-growth solution in which populations are maintained at near-constant levels is perfectly acceptable. This approach can be considered a complement to, rather than a replacement for, standard economic theory. It provides a different view of the productive economy that is in some ways more rigorous, as real physical constraints are always satisfied. In developing future scenarios, it also forces the modeler to be more transparent in framing their assumptions about social priorities for resource allocation.

To construct an explicit quantitative model, the hierarchical material dependencies between and within different economic sectors must be represented. Here a somewhat loose correspondence with the four food web categories (producers, herbivores, omnivores and carnivores) is described. A comparable division of the economy into four levels consists of consumption (in the usual economic sense), production of consumer goods, production of capital goods and primary or "natural" resources.

The top level consists of demand for material and energy services by the human population for personal consumption. The major consumption categories (analogous to species) are food, residential buildings, passenger transportation, resources used by the distribution system, and miscellaneous personal goods. Although human labor is an input at most of the levels, in a foodweb type model this input does not need to be accounted for explicitly. All animals perform some labor in securing their own food supply—the existence of the population implicitly assumes both the availability and the sufficiency of this labor power.

The two middle levels comprise all aspects of the productive economy including machinery, buildings, utilities, infrastructure, durable consumer goods *etc.* Roughly, the capital goods sector and most infrastructure development is comparable to herbivores, while manufacturing and such things as water and power utilities are more like omnivores. This reflects the fact that capital goods production depends heavily on primary resources and on other capital goods but only weakly on manufactured goods. Manufactured goods make heavy use both of primary resources and capital goods. In practice, the detailed definition of intermediate levels and their interactions will depend on the problem at hand.

The producer level in this framework comprises what is usually referred to as "the environment", which provides the economy with raw materials (including other living organisms), usable land, water, minerals and energy. Its important to be clear on the difference between energy and fuels in the primary resource category. What is meant here by energy is the set of renewable sources, which are actual fluxes of energy through the environment. These include solar radiation, kinetic energy from water and wind movement, and geothermal energy from naturally occurring hot water or steam. These energy sources can be utilized more or less effectively depending on technology. For the most part, they are not depleted by use, and their availability is outside human control.

The so-called non-renewable energy sources are really stocks of minerals that have been built up over millions of years, primarily fossil fuels and uranium. Their utility as energy depends on technology and is therefore intimately connected to the general state of the economy. Because they are stocks, they deplete over time. Estimates of total recoverable stocks of fossil fuels and minerals vary, but from a physical perspective the fact is that you start with a finite amount and from there it decreases monotonically. In practical terms, the limit is reached when the fuel consumed to obtain the resource is equivalent to the fuel produced. The equivalence is defined in energy terms, and so again will depend on the current state of technology and the degree to which different fuels can substitute for one another. Beyond this point, the only effect of further extraction will be to decrease the total amount of useful energy that is available to the economy. This simple conclusion is often obscured in practice by the fact that, in the real world, extractive industries are often tied up with complex ownership claims. Under these conditions, a net physical loss to the economy as a whole may still provide significant economic gains to some participants.

In an industrial economy, where direct foraging for fuel is negligible, biomass is *not* a renewable energy source supplied spontaneously by nature. To achieve the required output levels, biofuel feedstocks must be produced by industrial agriculture. This activity sits in the intermediate levels of an economic foodweb. Arable land, water, chemical fertilizers, capital goods and other energy-consuming inputs are required for biomass production. The availability of these inputs defines the total industrial agricultural production capacity. Hunger is a real and persistent problem in the world, and the question of whether or not biofuel production competes with food production is an important one. The answer depends on whether there is an excess of agricultural capacity above what is needed to supply the global population with adequate food. If there is not, it follows by simple logic that increasing the production of biofuel feedstock effectively displaces food production, even if the biofuel feedstock itself is not edible.

Questions about what is currently possible, and what will be possible or desirable in the future are extremely complex. A physically-based accounting of consumption needs and production capabilities, coupled to a realistic assessment of the physical constraints on both the scope and speed of potential new development, is a *minimal* requirement for effective decision making.